Chapter 16

Engineering Fundamentals: Part 1

Fluid Mechanics

16.1 Introduction

Fluid mechanics is a fundamental branch of civil, chemical, and mechanical engineering which deals with the behavior of liquids and gases, particularly while flowing. This chapter provides a brief review of the vocabulary and fundamental equations of fluid mechanics, and reminds the HVAC designer of the scientific principles underlying much of the day-to-day applied science calculations. See Ref. 1 or a fluid mechanics text for additional detail.

16.2 Terms in Fluid Mechanics

Many words are used in fluid mechanics which carry over into thermodynamics and heat transfer. A few of the fundamental terms are defined here for review.

Fluid: A liquid or a gas, a material without defined form which adapts to the shape of its container. Liquids are essentially incompressible fluids. Gases are compressible. Newtonian fluids are those which deform with a constant rate of shear. Water and air are newtonian fluids. Nonnewtonian fluids are those which deform at one rate of shear to a point and then deform at a different rate. Blood and catsup are nonnewtonian fluids.

Density ρ*:* Mass per unit volume, lbm/ft^3.

Viscosity μ: Resistance to shear, force · time/(length)^2.

Pressure P: Force per unit area.

Velocity V: Distance per unit time, ft/min, ft/s.

Laminar flow: Particles slide smoothly along lines parallel to the wall. Resistance to flow is proportional to the square of the velocity.

Turbulent flow: There are random local disturbances in the fluid flow pattern about a mean or average fluid velocity. Resistance to flow is proportional to the square of the velocity.

Reynolds number Re: A dimensionless number relating fluid velocity V, distance as a pipe diameter D, and fluid viscosity μ:

$$\mathrm{Re} = \frac{DV\rho}{\mu} \qquad \text{for a pipe}$$

Reynolds numbers below 2100 generally identify laminar flow. Reynolds numbers above 3100 identify turbulent flow. Reynolds numbers between 2100 and 3100 are said to be in a transitional region where laminar or turbulent conditions are not always defined.

Turbulent flow is desirable in heat exchange applications, while laminar flow is desired in clean-room and low-pressure-drop applications.

Cavitation: When the local pressure on a fluid drops below the vaporization pressure of the fluid, there may be a spot flashing of liquid to vapor and back again. Such a condition can occur with hot water at the inlet to a pump. Such activity is called *cavitation.* It can be harmful to the pump through local erosion and interference with flow. Cavitation often sounds like entrained gravel or little explosions at the point of occurrence.

16.3 Law of Conservation of Mass

Fluid mechanics starts with the *law of the conservation of mass* (see Fig. 16.1), which states, "Matter can be neither created nor destroyed." This gives us a chance to set up an accounting system for all flows in a system and to know that our accounts of inflows, outflows, and storage must balance at every point in the system.

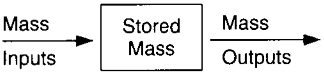

Figure 16.1 Conservation of mass.

16.4 The Bernoulli Equation (Law of Conservation of Energy)

Fluid mechanics studies focus on the Bernoulli equation (Navier-Stokes equations in more advanced mathematical analysis) which relates changes in energy in a flowing fluid (kinetic energy, potential energy, energy lost to friction, and energy introduced or removed) in terms of heat and work. If the study is observed over time, then all the terms are time-based and the work term is observed as power. The equation, similar to the conservation-of-mass equations, states that energy is conserved, that it cannot be destroyed, that it can be accounted for. See Fig. 16.2.

$$\frac{V_1^2 - V_2^2}{2} + g(h_2 - h_1) + \frac{1}{\rho}(P_2 - P_1) = \text{work}_{\text{in}} + Q_{\text{in}}$$

where V = velocity, g = gravitational constant, h = elevation, P = pressure, ρ = density, and Q is heat energy.

If this discussion seems somewhat theoretical, there are two brief equations derived from the above which are extremely useful in HVAC calculations. They are equations for estimating the theoretical horsepower of a fan or pump given the flow rate of water or air, the pressure drop to be overcome, and the nominal efficiency of the fluid-moving device.

For water:

$$\text{bhp} = \frac{\text{GPM} \times \text{head}}{3960 \times \text{eff}}$$

where GPM = water flow rate in gallons per minute, head = pressure rise across the pump in feet of water, eff = pump operating efficiency at calculation point, as a percentage, and the constant for water pumps is derived as follows:

$$\text{Constant} = \left(550\,\frac{\text{ft} \cdot \text{lb}}{\text{s} \cdot \text{hp}}\right)(60\ \text{s/min})\left(\frac{1\ \text{gal}}{8.33\ \text{lb}}\right) = 3960\left(\frac{\text{GPM} \cdot \text{ft}}{\text{hp}}\right)$$

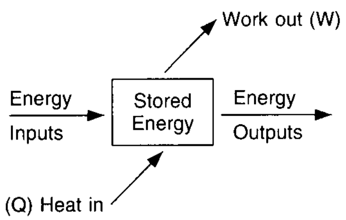

Figure 16.2 Conservation of energy.

For air:

$$\text{bhp} = \frac{\text{CFM} \times \text{SP}}{6356 \times \text{eff}}$$

where CFM = airflow rate in cubic feet per minute, SP = static pressure rise across the fan in inches of water, eff = fan operating efficiency at calculation point as a percentage, as for pumps, and the constant for fans is derived as follows:

$$\begin{aligned}\text{Constant} &= \left(550\ \frac{\text{ft} \cdot \text{lb}}{\text{s/hp}}\right)(60\ \text{s/min})\left(\frac{1\ \text{ft}^3}{62.3\ \text{lb}}\right)(12\ \text{in/ft})\\ &= 6356\left(\frac{\text{CFM} \cdot \text{in}}{\text{hp}}\right)\end{aligned}$$

In each case, the derivation of the constant term is shown to illustrate how keeping track of units can help to solve problems if the constant is forgotten or if the information is given in other units. Note that the liquid pumping horsepower will increase with higher-density liquids and can be accommodated by multiplying the equation by the relative density of the fluid pumped compared to water. The same is true of the air equation. CFM is assumed to be for standard air (0.075 lb/ft^3 at 60°F). If heavier gases or hot thin air or air at altitude is being handled, the equation must be corrected by the relative density. The air formula is only valid for a near-atmospheric-pressure condition (14.7 lb/in^2 gauge $\pm$ 1 lb/in^2, say). More variance than that invokes principles of compressibility, which adds complexity to the calculation.

Fluid mechanics addresses friction loss in piping and duct systems. It requires attention to differences in elevation for pumping of "open" systems and teaches us to recognize static-pressure concerns in both closed and open systems.

Static pressure problems with standing columns of air or other gas nearly always are associated with buoyancy effects of warmer versus colder gas, as in the induced *draft* of a chimney or the wintertime *stack effect* of a medium-rise or high-rise building.

16.5 Flow Volume Measurement

There are several different methods for measuring flow volume per unit time.

- *Direct liquid measurement:* This involves a mechanical measurement such as of the time required to fill a container of known volume or of observing the portion of a container filled in a given time.

- *Venturi meter:* A venturi is a smooth but constricted tube with pressure taps at the wide point and the necked point. Since there are no other effects, the change in static pressure from the wide to narrow sections can be used to determine velocity and flow volume (see Fig. 8.20 and related discussion).
- *Orifice plate meter:* An orifice plate is a plate with a carefully defined circular opening with a uniform edge characteristic. Laboratory measurement can identify a pressure drop across the plate for various flow rates. When the plate is installed between flanges with pressure taps, the field-measured pressure differential can be compared with the laboratory data to determine the flow rate (see Fig. 8.19 and related discussion).
- *Impact tube meter:* The total pressure in a flowing fluid is comprised of a velocity pressure component and a static or background pressure component:

$$P_t = P_{\text{vel}} + P_{\text{static}}$$

  If a tube is directed into the flowing fluid in the opposite direction it will read total pressure P_t. If a second tube is inserted parallel to the flow so that it sees no velocity impact, it will read the local static pressure. The static- and velocity-sensing tubes may be set up concentrically, forming a *pitot tube* (see Fig. 8.18 and related discussion). The difference between the total pressure and the static pressure is the local velocity pressure, and it can be converted to velocity for any given fluid. In the turbulent region, the velocity pressure is proportional to the square of the velocity.
- *Equipment as a meter:* Almost any device set in a moving fluid stream can be used as a coarse flowmeter since the pressure drop across the element is proportional to the square of the velocity. Heat exchangers are often calibrated for the flow rate. Cooling coils can be read on both the airside and waterside.

16.6 Summary

Fluid mechanics issues show up in nearly every aspect of HVAC systems design. Pumps, fans, coils, heat exchangers, refrigeration systems, process systems, boilers, deaerators, water softeners and treatment systems, water supply and distribution, building plumbing and fire protection, etc., are all grounded in the physics of fluid mechanics. There is a direct analogy between electrical concepts and fluid flow concepts. Consider Ohm's law—E (voltage) = I (current) × R (resistance)—and compare voltage to pressure, current to fluid flow, and

resistance to friction. Further recognize that storage of fluid in a tank is analogous to storage of electrons in a capacitor or inductive coil. An understanding of fluid mechanics leads to a rudimentary understanding of some aspects of electricity.

For further development of this topic, the reader is referred to the multitude of fluid mechanics textbooks or to the ASHRAE Handbook *Fundamentals,* which has a significant summarized presentation of the topic. For a hands-on data and reference book focused on hydraulics, see Ref. 2.

References

1. ASHRAE Handbook, *2001 Fundamentals,* Chap. 2, "Fluid Flow."
2. Ingersoll-Rand, *Cameron Hydraulic Data,* 17th ed., Woodcliff Lake, N.J., 1988.